

# The correlation between mid-latitude trough and the plasmopause

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[1] We use simultaneous global observations of the mid-latitude trough and the plasmopause to experimentally prove a long-standing conjecture of magnetosphere-ionosphere coupling- namely the mid-latitude trough and plasmopause are on the same field line. Global Ionospheric Maps (GIM), generated using ground based GPS receivers, are used to detect the globally extended mid-latitude trough; while global IMAGE EUV pictures are used to estimate the plasmopause position. Observations during the equinox and solstices and during quiet and disturbed periods are analyzed. In addition, positions of the mid-latitude trough are calculated using a simple empirical model. The two independent observations (mid-latitude trough and plasmopause positions) and an empirical model have been compared on a global scale and found to be in excellent agreement. **Citation:** Yizengaw, E., H. Wei, M. B. Moldwin, D. Galvan, L. Mandrake, A. Mannucci, and X. Pi (2005), The correlation between mid-latitude trough and the plasmopause, *Geophys. Res. Lett.*, 32, L10102, doi:10.1029/2005GL022954.

## 1. Introduction

[2] The mid-latitude trough (sometimes called the ionospheric trough) forms as a result of the stagnation of ionospheric plasma, trapped between a region of eastward (corotating) plasma drift, which is equatorward of the auroral zone [Whalen, 1989], and a region of westward drift in the auroral zone itself [Aladjev *et al.*, 2001].

[3] The concept of the plasmopause as a sharp gradient in the electron concentration in the equatorial plane is long-standing and familiar. The plasmopause marks the outer boundary of the plasmasphere, a region of ionospheric origin plasma which co-rotates with the Earth carried by the magnetic field lines [Moldwin, 1997].

[4] Despite much progress in the last decades, many gaps exist in our understanding of these regions. For example, the correlation between the ionospheric mid-latitude trough and plasmopause has not been viewed on global scales due to the lack of global snapshots of ionospheric measurements and the plasmopause. Many early studies argued that the mid-latitude trough and the projection of the plasmopause onto ionospheric altitudes are near the same field line. Many attempts have been made to prove this argument experimentally by observing the two features simultaneously [Grebowky *et al.*, 1976; Sivtseva and Ershova, 1978;

Rodger and Pinnock, 1982; Smith *et al.*, 1987]. However, none of these studies have shown a definite relation between the two features nor made a global comparison between them.

[5] This paper, which presents a global comparison of the two features for the first time, clearly addresses the following questions: What is the correlation between the mid-latitude trough and the location of the plasmopause? Is the hypothesis that we have been using, i.e., the two features are on the same field line, true?

## 2. Data Analysis

[6] The Jet Propulsion Laboratory (JPL) has created global ionospheric maps (GIM) of the total electron content (TEC) at sub-hourly intervals [e.g., Mannucci *et al.*, 1998] using a continuously operating global network of Global Positioning System (GPS) receivers. The vertical TEC, extracted from dual frequency GPS receivers using standard GPS TEC extraction techniques [e.g., Sardón *et al.*, 1994], are interpolated in both space and time to produce the global TEC maps. Such spatial interpolation is possible using pixel-based methods, where widely separated regions can be retrieved independently of each other. The TEC predictions from climatological models are also incorporated as simulated data to bridge significant gaps between measurement data. Mannucci *et al.* [1998] have clearly described these special interpolation techniques of vertical TEC.

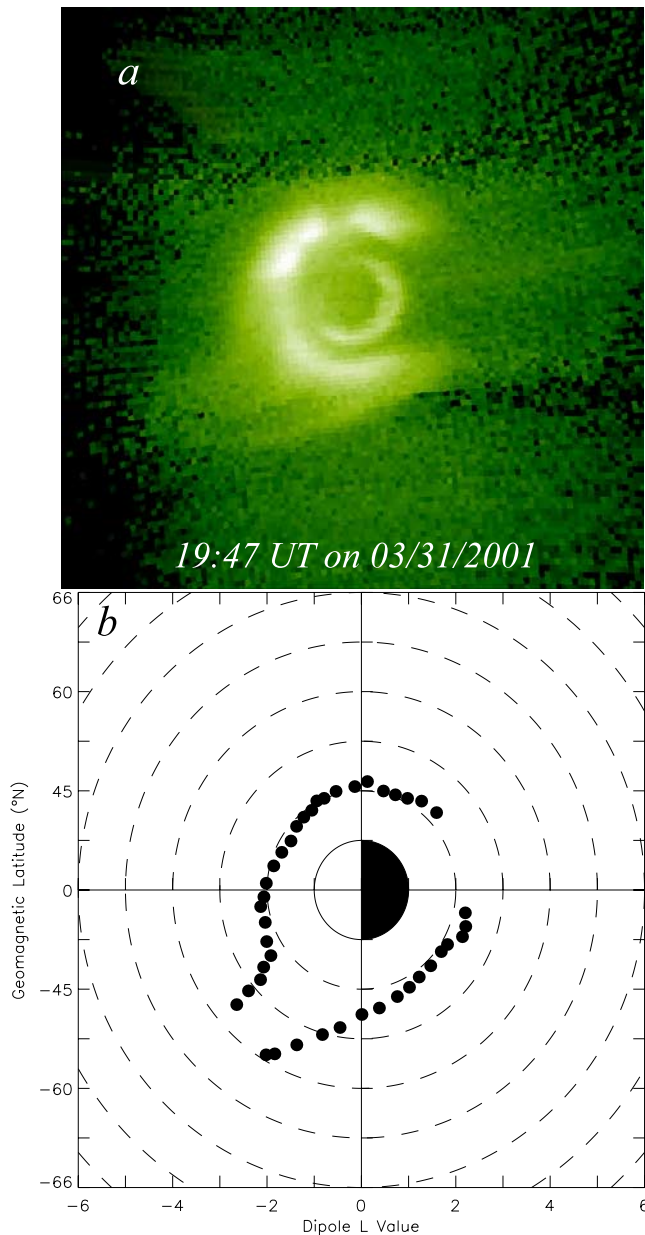
[7] The IMAGE EUV satellite routinely provides global snapshots of the plasmasphere with spatial and temporal resolution of about 0.1  $R_E$  and  $\sim 10$  min respectively [Goldstein *et al.*, 2004]. This allows the global position of the plasmopause to be determined from each snapshot of the IMAGE EUV images. We extracted plasmopause locations manually from several EUV snapshots taken in 2001 by clicking on an EUV image with a computer mouse along the plasmopause with an average azimuthal spacing of about an hour of magnetic local time (MLT) [Goldstein *et al.*, 2004]. Figure 1a shows a typical example of an EUV snapshot image. The corresponding manually extracted plasmopause location, which is plotted versus latitude in the ionosphere and versus L value in the equator, is shown in Figure 1b.

## 3. Observations

[8] Although it is an interpolated ionospheric map, the main ionospheric features such as the ionospheric mid-latitude trough and plasmaspheric plume signature [Foster *et al.*, 2002] are readily identified by GIM. To magnify the mid-latitude trough, we identify four to six quiet days of each month and calculate the percentage difference between

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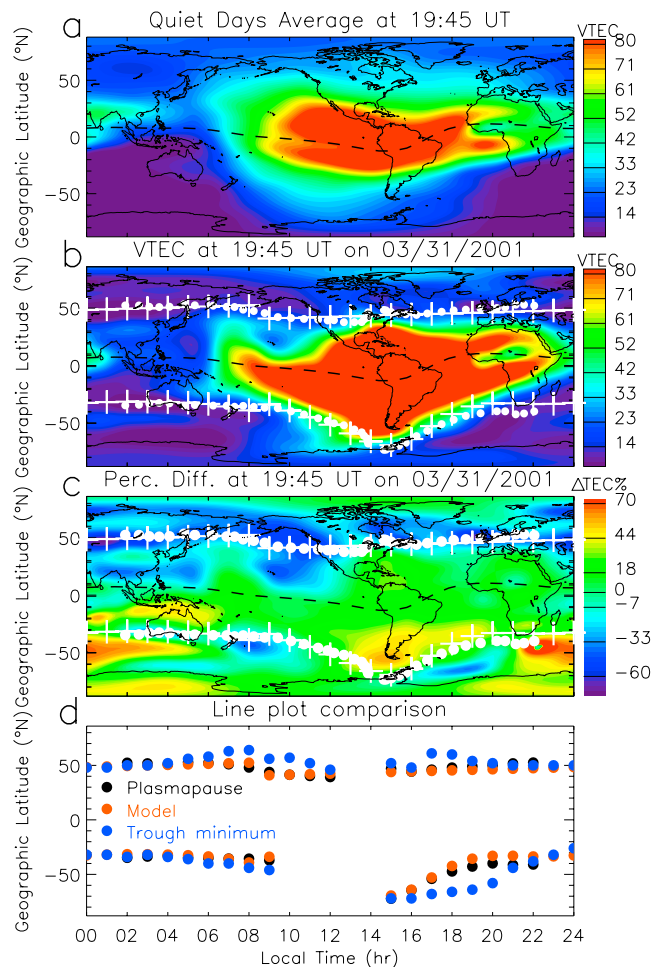


**Figure 1.** (a) Example of plasmaspheric image, which is mapped to the magnetic equator (Earth at the center and Sun to the left), as seen by IMAGE EUV at the time and date given at the bottom of the panel, and (b) filled black circles are manually extracted points along the plasmapause from the EUV snapshot in Figure 1a.

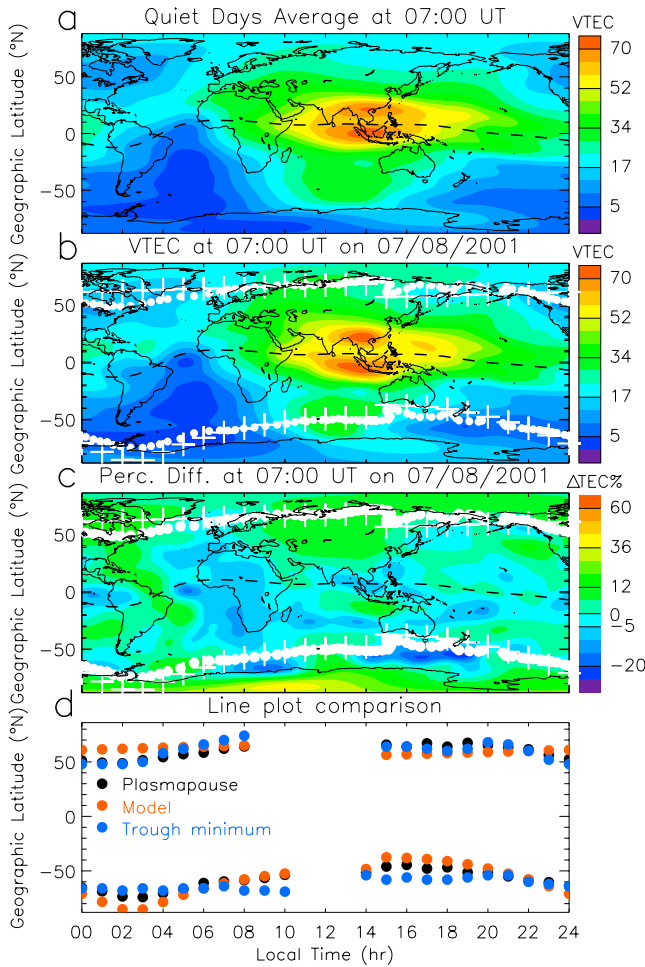
the actual data at a given time and the average value of vertical TEC of those quiet days. We perform such plots for every 15-minute interval. Typical examples of the global ionospheric maps in Figures 2a and 2b, respectively, show a 15-min quiet days' average and a 15-min average actual ionospheric TEC map centered at 19:45 UT on 31 March 2001. Percentage differences between Figures 2b and 2a are also shown in Figure 2c. The locations of trough minimum points are extracted manually and are compared with plasmapause positions in a quantitative way as shown in Figure 2d. March 31, 2001 was the first day of a large geomagnetic storm; at 09:00 UT,  $Dst \approx -387$  nT

and  $Kp > 8$ . (For more about the 31 March 2001 storm, see *Yizengaw et al.* [2005]). As can be seen in Figure 2, the ground based observations show a deep mid-latitude trough extending globally and a signature of the plasmaspheric plume over North America. GIM maps detected the equatorward and poleward edges of the mid-latitude trough and the auroral oval indicated by the fine-scale TEC enhancement (which is more clearly seen in the percentage difference maps).

[9] The plasmapause positions (white dots), which are estimated from IMAGE EUV, are over plotted on the global GPS VTEC plots as shown in Figures 2b and 2c. The plasmapause projections onto the ionosphere, especially during daytime, lie at the equatorward edge of the mid-latitude trough, whereas during nighttime they are mostly projected onto the trough minimum. This is clearly visible in Figure 2d. Interestingly, GIM's plasmaspheric plume signature over North America and the plume extension,



**Figure 2.** The 15-minute average global contour maps of GPS TEC: (a) six quiet days average (b) actual data on 31 March 2001 (c) the percentage difference between Figures 2a and 2b. The white dots and plus sign in Figures 2b and 2c, respectively, depict the plasmapause locations and the empirical positions of the mid-latitude trough. (d) quantitative comparison of trough minimum, plasmapause locations and empirical positions of mid-latitude trough.



**Figure 3.** As for Figure 2 but for magnetically quiet day on 8 July 2001 at 07:00 UT.

extracted from EUV image, coincided nicely as shown in Figures 2b and 2c.

[10] Figure 3 is another typical example of global simultaneous observation of mid-latitude trough and plasmopause ionospheric projection, representing magnetically quiet day ( $K_p < 3$ ) observations. July 8, 2001 corresponded to a  $K_p$  value of less than 3, and as such the percentage difference map (Figure 3c) does not magnify the trough-like structure very well as it does during disturbed times. However, a clear trough-like structure which extends from post noon to pre noon is detected by GIM in the southern hemisphere (winter) as shown in Figure 3b. There is also a signature of a trough-like structure, which extends from post noon to the post midnight sector, in the northern hemisphere (summer) as well; however, it is not as deep as the trough shown in the winter hemisphere. The projection of the plasmopause onto the ionosphere (white dots) shows good agreement with the mid-latitude trough observed by GIM.

[11] IMAGE EUV has detected the density cavity found in the plasmopause profile, which is usually called a “notch”, and its projection on the ionosphere appears to be the equatorward extended plasmopause signature over south-west Australia as shown in Figures 3b and 3c. During this quiet period observation, both mid-latitude trough and plasmopause projections appeared at higher latitude com-

pared to their positions during the disturbed period shown in Figures 2b and 2c. The quantitative comparison of trough minimum and plasmopause is also shown in Figure 3d.

[12] The positions of the trough minimum as a function of planetary magnetic activity index ( $K_p$ ) and local time ( $t$ ) are calculated empirically using the relation given by  $\Lambda_T = 65.2^\circ - 2.1K_p - 0.5t$  [Moffett and Quegan, 1983]. Where  $\Lambda_T$  is the trough invariant latitude and  $t$  is the time in hour from midnight local time (positive after midnight and negative before midnight); the range of data is such that  $-15 \leq t < 9$  hours. Using the appropriate local time and  $K_p$  value, the empirical position of the trough is computed and plotted over the GIM global maps indicated by white plus sign in Figures 2 and 3. The empirical position of mid-latitude trough agreed very well with the mid-latitude trough and plasmopause positions.

[13] Meanwhile, the GIM maps revealed hemispheric differences in the ionospheric density structures in general and in the mid-latitude trough appearance in particular. The depth and width differences in the mid-latitude trough between the north and south are also evident as shown in the typical examples given in Figures 2 and 3.

#### 4. Discussion

[14] Particle precipitation and redistribution of the resulting plasma by the action of the convection electric field have been shown to be of primary importance in the formation of the poleward edge of the mid-latitude trough [Moffett and Quegan, 1983; Whalen, 1989]. On the other hand, the location of the plasmopause is mainly controlled by the magnitude of the convection electric field [Rodger and Pinnock, 1982]. For these reasons one might expect a close relationship between the mid-latitude trough and the plasmopause.

[15] Even though quite a few simultaneous observations have been conducted, they have not pointed to a common conclusion. Most observations also have been performed only at a specific area and have made several major assumptions. The first assumption was that the two features are quasi-stationary in the Sun-Earth frame of reference, and the second was that the continually varying convection electric field is the main influencing force to the formation of the mid-latitude trough. However, these assumptions are questionable and lead to wide dissimilarities of the two features. Since the magnitude of the convection electric field is continually changing, particularly during and immediately after magnetospheric storms, the first assumption does not hold under disturbed conditions. In the case of the latter assumption, there are many other additional processes which influence the distribution of ionospheric plasma in the vicinity of the trough. For example, there are significant local increases in the recombination rates for atomic oxygen resulting in variations of composition [e.g., Yizengaw *et al.*, 2005]. Effects caused by thermospheric winds also play a significant role. Finally, an outflow of heavy ions such as atomic oxygen can have significant effect [Winglee *et al.*, 2002].

[16] In this global comparison study, we have carried out about 40 simultaneous observations in four months (March to July 2001), depending on the limited data available from IMAGE EUV. Most ( $\sim 85\% - 92\%$ ) of the global simulta-

neous observation of the two features that we performed during both magnetically disturbed and quiet periods show good agreement and prove the hypothesis that the two features lie on the same field line. As can be seen in the typical observations during a magnetically disturbed period (Figure 2) and quiet period (Figure 3), the plasmopause position lies at the equatorward edge of the mid-latitude trough, especially at the dayside trough. This position of the plasmopause was expected, because our manual extraction method estimated the minimum L-value of the plasmopause. Furthermore, the plasmopause position as determined from IMAGE EUV has a position uncertainty of  $\leq 0.4$  L on the dayside and  $\sim 0.1$  L on the nightside where the plasmopause gradient is steep [Goldstein *et al.*, 2004]. Unlike the earlier works [Rodger and Pinnock, 1982; Smith *et al.*, 1987] our global comparison is not local time dependent. Rodger and Pinnock [1982] and Smith *et al.* [1987] found that the two features are widely separated by as much as 2 L ( $\sim 11^\circ$  in latitudes) in the evening hours. However, our global comparisons (both during disturbed and quiet times) show that the separations between the plasmopause and the equatorward edge of the trough are less than  $5^\circ$  in the dayside with almost no separation during nighttime. Furthermore, the plasmopause separation from the manually extracted trough minimum (Figures 2d and 3d) did not exceed  $\sim 10^\circ$  in latitude. Note that the GIM grid is very coarse and the product is obtained through certain smoothing, which reduces the spatial resolution further. Thus the trough width and trough minimum derived here might be affected and the real-world trough minimum and plasmopause separation may be quite less  $10^\circ$ . These clearly confirm that our comparison is local time independent and reliable to assure that the mid-latitude trough is field-aligned with the plasmopause. An extraordinary agreement (see Figure 2) between the plasmaspheric plume signature and the plasmopause locations along the finger-like plume structure is also another important validation for our simultaneous observation of the two features. Similarly a density cavity in the plasmopause profile (“notch”), which is believed to be associated with a weaker convection electric field and the late evolution of plasmaspheric plumes, is projected south-west of Australia as shown in Figure 3.

[17] The two features’ comparisons presented in Figure 2, which are performed during the 31 March 2001 severe storm, show that the mid-latitude trough lies at lower latitudes than during magnetically quiet periods shown in Figure 3. This illustrates two major physical phenomena: the equatorward expansion of the auroral oval (as the mid-latitude trough follows the movement of the expanding auroral oval), and the compression or erosion of the plasmasphere (as the plasmopause is projected onto the ionosphere at lower latitude). Foster *et al.* [2002], using ground based GPS TEC and IMAGE EUV snapshots, clearly demonstrated dramatic plasmaspheric erosion during this severe storm. At the same time the auroral particles and imagery shows (not shown here) that the auroral oval was expanded to lower latitudes. The location of the trough derived from a simple empirical formula, as shown by white plus signs in Figures 2 and 3, shows good agreement with the mid-latitude trough and the plasmopause locations (white dots).

[18] Although the two features agree very well both at the north and southern hemisphere, there is quite a large difference in ionospheric density structure between conjugate hemispheres. This could be due to a larger offset between geographic and geomagnetic poles in the south. Such an offset can create hemispherical differences in the Earth’s polar environment and thus a marked difference in the ionospheric density and thus mid-latitude trough structure between the conjugate hemispheres [Fuller-Rowell *et al.*, 1987]. A detail study of such hemispheric differences in electron density distribution and mid-latitude trough structure is the subject of another paper.

## 5. Summary

[19] The study of the simultaneous global positions of the mid-latitude trough and the plasmopause show excellent agreement, implying that the two features lie on the same field line. Such excellent agreement demonstrates the potential of both GIM and IMAGE EUV, which precisely determines the location of the mid-latitude trough and plasmopause respectively. The good agreement of the empirical positions of the mid-latitude trough with experimentally determined trough and plasmopause projections are another important result in modeling the plasmopause position at ionospheric heights. Although quite a few simultaneous position observations have been performed earlier, such a global comparison has never been reported before and we believe that the present study has clearly demonstrated and experimentally confirmed the long-standing hypothesis that the two features lie on the same field lines.

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